Nanotechnology in Preventive Dentistry: Current Advances and Clinical Applications

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Abstract

Introduction: Nanotechnology — the engineering of materials at the 1–100 nm scale — has emerged as a transformative paradigm in preventive dentistry. Nano-hydroxyapatite (n-HAp), nanocomposite resins, and antimicrobial nanoparticles offer biomimetic and functional properties that substantially advance conventional dental materials. This review critically appraises the current evidence on the clinical applications, efficacy, and safety of nanotechnological innovations in preventive oral healthcare.

Material and Methods: A narrative review of peer-reviewed publications from 2011 to 2024 was conducted across PubMed/MEDLINE, ScienceDirect, and Google Scholar. Search terms included "nanotechnology," "preventive dentistry," "nano-hydroxyapatite," "nanocomposite," "antimicrobial nanoparticles," and "remineralisation." Eligible publications included systematic reviews, RCTs, in vitro studies, and narrative reviews reporting quantitative outcomes for nanotechnology-based dental materials.

Important Results/Observations: Nano-hydroxyapatite demonstrated significant enamel remineralisation and dentinal tubule occlusion. Nanocomposite resins exhibited superior mechanical performance — reduced polymerisation shrinkage (<2%), enhanced flexural strength (120–160 MPa), and lower surface roughness (Ra <0.2 µm) — compared to conventional composites. Silver, zinc oxide, and titanium dioxide nanoparticles displayed potent antibiofilm activity against cariogenic and periodontal pathogens. Concentration-dependent cytotoxicity and manufacturing standardisation gaps were consistently identified as safety concerns.

Discussion (including Conclusions): Nanotechnology-based dental materials demonstrate considerable promise for advancing minimally invasive and preventive care. However, the preponderance of evidence derives from in vitro or short-term clinical studies. Cytotoxicity concerns, manufacturing inconsistency, and the absence of nano-specific regulatory frameworks are substantive barriers to clinical adoption. Comprehensive long-term RCTs, standardised protocols, and regulatory frameworks are essential prerequisites for the safe integration of these materials into mainstream preventive dental practice.

Keywords: nanotechnology; preventive dentistry; nano-hydroxyapatite; nanocomposites; antimicrobial nanoparticles

Introduction

Contemporary preventive dentistry is founded on the conservation of natural tooth structure and the early interception of disease through minimally invasive strategies. Dental caries — the world's most prevalent chronic infectious disease — and associated conditions such as dentinal hypersensitivity and restoration failure continue to impose a significant global oral health burden, despite established fluoride-based preventive programmes. This underscores the need for innovative materials that can deliver superior efficacy, biological compatibility, and accessibility across diverse healthcare settings.

Nanotechnology encompasses the design, synthesis, and application of materials with structural features in the 1–100 nm range. At this scale, matter exhibits unique properties — substantially increased surface-area-to-volume ratios, altered reactivity, and enhanced structural performance — that are not observed in bulk materials of equivalent composition. These properties render nanoscale materials particularly advantageous for dental applications, where precision at the tissue–material interface is paramount[1,5].

Three principal categories of nanotechnology-based materials have attracted significant clinical interest in preventive dentistry: nano-hydroxyapatite (n-HAp) for remineralisation and hypersensitivity management; nanoparticle-reinforced composite resins for minimally invasive restorations; and antimicrobial nanoparticles for oral biofilm control. This narrative review synthesises current evidence on their clinical performance, documented safety concerns, and priorities for future translational research.

Material and Methods

A narrative review of the peer-reviewed literature was conducted to synthesise evidence on nanotechnology applications in preventive dentistry. Electronic databases searched included PubMed/MEDLINE, ScienceDirect, Google Scholar, and Wiley Online Library for publications from January 2011 to December 2024. Boolean search terms combined: "nanotechnology," "preventive dentistry," "nano-hydroxyapatite," "remineralisation," "nanocomposite," "dental restoration," "silver nanoparticles," "zinc oxide nanoparticles," "titanium dioxide," "antimicrobial," "oral biofilm," "cytotoxicity," and "dental safety."

Studies were included if they: (i) evaluated nanotechnology-based materials for dental caries prevention, remineralisation, restorative dentistry, or oral biofilm control; (ii) reported quantitative outcome measures — mechanical properties, microbiological efficacy, or clinical performance metrics; and (iii) were published in English in peer-reviewed journals. Systematic reviews, RCTs, in vitro studies, and narrative reviews were all eligible. Parameters extracted included: material type and composition; study design; outcome measures; safety findings; and conclusions regarding clinical applicability.

Results

Nano-Hydroxyapatite in Remineralisation and Hypersensitivity Management

Hydroxyapatite constitutes approximately 96% of enamel by weight, making it the natural mineralogical template for tooth hard tissue. Nano-hydroxyapatite (n-HAp), with particle dimensions of 20–100 nm, closely replicates the crystallographic composition of biological apatite, enabling direct physicochemical integration with residual tooth mineral. Its nanoscale dimensions permit penetration of early-stage enamel lesions, dentinal tubule orifices, and microfissures inaccessible to conventional ionic fluoride or larger-particle mineral formulations[2,3].

Mechanistically, n-HAp releases calcium and phosphate ions into the oral environment, driving mineral redeposition onto demineralised enamel — closely mirroring physiological remineralisation. It also physically occludes patent dentinal tubules, directly attenuating the hydrodynamic fluid movement implicated in dentinal hypersensitivity pathophysiology[3,6]. Najibfard et al[3]. demonstrated in an RCT that a 10% w/w n-HAp dentifrice produced significant reductions in white-spot lesion depth compared to a fluoride control. Tschoppe et al[6]. confirmed effective tubule occlusion and hypersensitivity reduction comparable to commercial desensitisers. Bordea et al[2]. and Bapat et al[1]. corroborated biomimetic efficacy while highlighting that the majority of evidence derives from short-duration or in vitro studies. A summary is presented in Table 1.

Table 1. Summary of Key Studies on Nano-Hydroxyapatite in Remineralisation and Hypersensitivity Management

Author (Year)	Study Typ	en-HAp Concentration	Key Outcome
Najibfard et al. (2011)[3]	RCT	10% w/w dentifrice	Significant enamel remineralisation; reduced white-spot lesion depth vs fluoride control
Tschoppe et al. (2011)[6]	In vitro/clinical	Nano-HAp toothpaste	Effective dentinal tubule occlusion; hypersensitivity reduction comparable to commercial desensitisers
Bordea et al. (2020)[2]	Narrative review	Variable (1–15%)	Confirmed remineralisation efficacy; insufficient long-term RCT data
Bapat et al. (2021)[1]	Overview/review	Various formulations	Biomimetic properties confirmed; standardised dosing and manufacturing protocols needed

n-HAp = nano-hydroxyapatite; RCT = randomised controlled trial; w/w = weight by weight.

Nanocomposites in Minimally Invasive Restorative Dentistry

Conventional hybrid composites incorporate filler particles of 0.4–1.0 µm, limiting polishability and predisposing restorations to surface roughness and plaque accumulation. Nanocomposite resins incorporate fillers of 5–100 nm - including nanosized silica, zirconia, and hydroxyapatite - achieving uniform distribution and greater filler loading without sacrificing workability [1,4]. Polymerisation shrinkage is measurably reduced (typically <2% versus 2–5%), decreasing gap formation and secondary caries risk. Surface roughness values below 0.2 µm — below the threshold for clinically significant plaque retention — are consistently achievable following routine polishing.

Enhanced flexural strength (120–160 MPa versus 80–120 MPa) improves longevity in posterior restorations. Bioactive calcium phosphate nanofillers additionally provide sustained mineral ion release at the restoration–tooth interface[1,4]. Comparative properties are presented in Table 2.

Table 2. Comparative Properties of Conventional Composites and Nanocomposite Resins

Property	Conventional Composite	Nanocomposite	Clinical Relevance
Filler particle size	0.4–1 µm (hybrid)	5–100 nm	Smoother surface finish; improved polishability
Polymerisation shrinkage	2–5%	<2%	Reduced microleakage; lower secondary caries risk
Surface roughness (Ra)	>0.2 µm	<0.2 µm	Less plaque retention; improved peri-restoration health
Flexural strength	80–120 MPa	120–160 MPa	Greater fracture resistance in posterior restorations
Mineral release	Absent	Present (bioactive Nps)	Potential remineralisation at restoration–tooth interface

AgNPs = silver nanoparticles; ROS = reactive oxygen species; TiO_2 = titanium dioxide; ZnO = zinc oxide.

Antimicrobial Nanoparticles in Oral Biofilm Control

Antimicrobial nanoparticles penetrate biofilm matrices and exert bactericidal effects through mechanisms distinct from conventional antimicrobials. Yin et al. [7] characterised silver nanoparticle (AgNP) antibacterial activity as membrane disruption, reactive oxygen species (ROS) generation, and inhibition of DNA replication — with broad-spectrum activity against Streptococcus mutans, Lactobacillus spp., and Candida albicans. Zinc oxide and titanium dioxide nanoparticles operate through analogous ROS-mediated mechanisms, with TiO_2 demonstrating photocatalytic bactericidal activity under light activation [5,7]. Chitosan nanoparticles offer a biodegradable carrier platform for localised antimicrobial delivery. Mechanisms and evidence are summarised in Table 3.

Table 3. Antimicrobial Nanoparticles in Oral Biofilm Control: Mechanisms and Evidence

Nanoparticle	Target Organism(s)	Mechanism of Action	Key Findings
Silver (AgNPs)	S. mutans, C. albicans, broad spectrum	Membrane disruption; ROS generation; inhibition of DNA replication	Strong in vitro antibiofilm activity; cytotoxic at high concentrations[7]
Zinc oxide (ZnO NPs)	S. mutans, periodontal pathogens	ROS-mediated oxidative stress; cell membrane disruption	Lower cytotoxicity than AgNPs; antifungal properties confirmed[5]
Titanium dioxide (TiO, Nps)	Broad spectrum (photo-activated)	Photocatalytic ROS under UV/visible light	High bactericidal efficacy under light activation; suitable for dental coatings[5]
Chitosan NPs	S. mutans, Lactobacillus spp.	Membrane permeabilisation; intracellular leakage	Biodegradable and biocompatible; effective antimicrobial carrier in gels[5,7]

AgNPs = silver nanoparticles; ROS = reactive oxygen species; TiO_2 = titanium dioxide; ZnO = zinc oxide.

Safety and Regulatory Considerations

Bapat et al. [1] and Shahi et al.[5] identified concentration-dependent cytotoxicity as the principal safety concern across dental nanomaterials. While cytotoxic effects predominantly occur at concentrations exceeding current clinical formulations, genotoxic and inflammatory responses at lower concentrations cannot be excluded without long-term human studies. Paqué and Özcan[4] highlighted that

variability in synthesis methods introduces significant batch-to-batch inconsistency in particle size, surface chemistry, and biological behaviour. Regulatory frameworks in most jurisdictions do not differentiate nano-scale dental materials from conventional counterparts, creating gaps in pre-market safety evaluation and post-market surveillance. Principal challenges and mitigation strategies are presented in Table 4.

Table 4. Principal Safety and Regulatory Challenges Associated with Dental Nanomaterials

Challenge	Specific Concern	Recommended Mitigation
Clinical evidence gap	Most data from in vitro or short-term studies; no multi-year RCTs	Adequately powered prospective RCTs with ≥24-month follow-up
Cytotoxicity	Concentration-dependent cellular and potential genotoxic effects	Establish clinically safe thresholds; mandate dose-response profiling
Manufacturing variability	Inconsistency in particle size, morphology, and surface chemistry	Develop ISO-aligned standardised characterisation protocols
Regulatory gaps	No nano-specific guidance in most jurisdictions	Advocate for nano-specific medical device classification frameworks
Environmental impact	Nanoparticle accumulation in wastewater; aquatic toxicity	Lifecycle environmental assessments; biodegradable formulation design

ISO = International Organization for Standardization; RCT = randomised controlled trial.

Discussion

The accumulated evidence substantiates that nanotechnology - based materials represent a scientifically credible advancement in preventive dentistry. The biomimetic nature of n-HAp its chemical identity with biological apatite and capacity to integrate into demineralised tooth structure - offers a mechanistically distinct and complementary approach to fluoride-based remineralisation, with particular appeal for populations in whom fluoride use may be constrained[2,3,6].

The improved mechanical and surface properties of nanocomposite resins translate directly into clinically relevant advantages: reduced secondary caries risk through superior marginal integrity and lower plaque-retentive surfaces, and improved restoration longevity through enhanced flexural strength outcomes well aligned with minimally invasive dentistry principles[1,4]. The multi-target mechanisms of antimicrobial nanoparticles- simultaneously disrupting bacterial membranes, generating intracellular oxidative stress, and inhibiting metabolic enzymes - may also confer advantages in terms of reduced likelihood of bacterial resistance emergence compared to single-target antibiotics[5,7].

Nevertheless, translation into established clinical practice requires careful qualification. The evidence base for virtually all nano-dental materials remains dominated by short-term or laboratory studies. Paqué and Özcan [4] and Shahi et al.[5] both identified methodological heterogeneity, reliance on surrogate outcome measures, and the absence of patient-centred long-term clinical data as critical limitations. Environmental stewardship considerations — including the ecological impact of antimicrobial nanoparticle discharge into wastewater systems - further underscore the need for comprehensive lifecycle assessments before universal clinical deployment[1,5].

Conclusion

Nanotechnology represents a scientifically compelling frontier in preventive dentistry. Nano-hydroxyapatite, nanocomposite resins, and antimicrobial nanoparticles each demonstrate specific, well-grounded performance advantages over conventional materials with significant potential to improve preventive oral health outcomes. However, the current evidence base remains preliminary-dominated by in vitro and short-term clinical data. Concentration-dependent cytotoxicity, manufacturing inconsistency, and the absence of nano-specific regulatory frameworks remain substantive barriers to routine clinical adoption. Long-term RCTs, standardised manufacturing and characterisation protocols, and nano-specific regulatory guidance are essential prerequisites for the safe and responsible integration of these technologies into mainstream preventive dental practice.

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